# SCIENCE FOR GLASS PRODUCTION

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## EFFECT OF PORE SIZE ON HEAT FLOWS IN THERMAL TREATMENT OF FOAM GLASS

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The results of studying the specifics of heat transfer processes in porous heat-insulating materials at high temperatures are described. The effect of the pore size on the type of heat transfer in glass-based porous materials is considered; recommendations on methods for analyzing heat transfer in materials with sealed porosity are provided.

Although foam glass has long been used as a construction material, it is not sufficiently studied.

When foam glass is produced by the foaming method by means of heat treatment of a batch containing inorganic glass and a blowing agent (coal, coke, etc.), the specifics of heat exchange in a foam glass sample in annealing (which is the longest and the most energy-consuming operation affecting the product quality) are of special interest.

The main feature of the foam glass structure is its high content of the gaseous phase (specific porosity is approximately 92% for material density around 200 kg/m$^3$); therefore, heat transfer is implemented in two ways: via the material (glass) and via the gaseous medium [1].

Heat transfer in a material comprising the matrix of a porous body (conductive heat transfer) proceeds by heat conductance. The quantity of energy transferred in this way is determined by the Fourier law and depends on the heat conductivity of the material (in our case, glass), the distance between the pore walls (the pore size), and the thickness of the interpore partitions.

Heat transfer in a gaseous medium is complicated due to the presence of several transfer methods.

First, the gaseous medium is a transparent (or semitransparent) medium; therefore, radiation heat transfer is implemented by electromagnetic radiation whose energy is generated by thermal motion exciting atoms, molecules, and other particles of the porous body matrix. The radiation from the body surface is determined by the radiating capacity of the material (glass) and is related to its temperature (the higher the temperature, the more intense the radiation). The radiation is transferred to another surface across the dividing space filled with a gaseous medium which absorbs and transmits radiation depending on the type and extent of this medium [2].

In our case we are dealing with foam glass, in which the foaming agents are carbon-bearing materials (coal, coke, etc.); therefore, the gaseous medium has a high content of carbon dioxide. The latter is a three-atom gas capable of absorbing part of the radiation spectrum of thermal radiation. In accordance with Kirchhoff's law, such gases have a radiating capacity; therefore, in analyzing heat transfer in foam glass one has to take into account the radiation properties and the volume (determined by the pore size) of the gaseous medium.

Second, heat transfer in a gaseous medium is implemented by the gas molecules (actually the thermal conductivity of gas). This type of transfer depends on the motion of the molecules and this in turn depends on the presence of gas condensation. Under moderate and high temperatures there is no condensation of the gaseous phase in foam glass; consequently, the thermal conductivity of the gaseous medium depends on the thermal conductivity of the gas mixture and the pore sizes.

There is also a third type of transfer in a gaseous medium, i.e., convection, where thermal conductance processes are related to the motion of the total gas mass. Due to this motion, the intensity of heat transfer determined by thermal conductivity in many cases substantially changes.

Convection inevitably coexists with thermal conduction, since, although the motion of particles modifies the heat transfer process, the final transfer of energy from one gas element to an adjacent one is implemented via thermal con-

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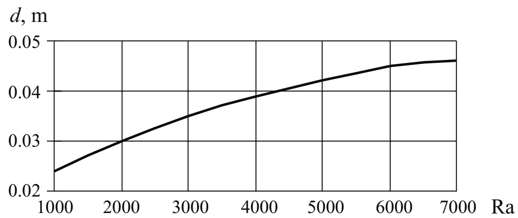


**Fig. 1.** Dependence of the distance between the layers on the Raleigh number.

duction. Thus, convection heat transfer also includes thermal conductivity and sometimes radiation processes as well related to the motion of gas. Therefore, the calculation of the quantity of heat transferred by convection is complex and labor-consuming.

Convective motion is directly related to the position of the warmer and colder gas layers. If the gas contained in pores is heated from beneath, heat is transferred from the bottom to the top surface. As a result, the cold (denser) gas layers are located above the warmer (less dense) layers, which generates thermal instability and may lead to the formation of convection flows.

Thus the problem of analyzing convection flows is reduced to analysis of thermal instability and can be studied using the stability analysis method.

It is known that convection currents are not formed (the system continues thermally stable) as long as the Raleigh number is below a certain critical level whose theoretical number is equal to approximately 1700 [3].

The Raleigh number is determined by the formula

$$\mathrm{Ra} = \frac{g \beta_g d^3 (t_1 - t_2)}{\nu \alpha_g}, \tag{1}$$

where $g$ is the free fall acceleration; $\beta_g$ is the temperature coefficient of the volumetric expansion of gas; $d$ is the distance between the surfaces restricting the gaseous space (actually the diameter of foam glass pores); $t_1$ and $t_2$ are the surface temperatures; $\nu$ is the kinetic viscosity; and $\alpha_g$ is the thermal conductivity of gas.

If the properties of the materials used in foam glass production are constant, the Raleigh number (and accordingly, the stability of the system) depends only on the surface temperatures and the distance between the surfaces.

However, the difference between the surface temperatures as well indirectly depends on the properties of the material (glass), since a temperature difference produces stresses in the glass matrix of foam glass caused by different thermal expansion of the surfaces. Thus, we can speak of a critical temperature difference under which the arising stresses exceed the admissible values and this leads to the fracture of the sample. Hence $\Delta t$ should satisfy the following relationship:

$$\Delta t \le \frac{[\sigma_{ad}]}{E \beta_g}, \tag{2}$$

where $\beta_{gl}$ is the temperature coefficient of the volumetric expansion of glass.

By substituting inequality (2) in Eq. (1) we will get a relationship which the Raleigh number has to satisfy in order not to disturb the integrity of the porous material:

$$\mathrm{Ra} \le \frac{[\sigma_{ad}] g \beta_g d^3}{E \beta_g \nu \alpha_g}.$$

It follows from this formula that when the materials used have constant properties, the thermal stability of the system depends only on the distance between the surfaces and should not exceed a certain level that is critical for foam glass strength.

Figure 1 shows the dependence of the pore diameter on the Raleigh number, other properties of the foam glass being equal.

Consequently, for convection currents to be formed in the pore space of foam glass ($\mathrm{Ra} \ge 1700$) and at the same time to prevent the fracture of the sample, the distance between the layers (actually the pore diameter) should be more than 0.027 m (27 mm). In this case the contribution of these currents in the heat exchange between the layers is low. In order to form laminar currents, the distance between the layers should be extended to 0.037 m, not to mention turbulence, which requires a distance of 0.240 m.

The pores in foam glass used for construction purposes are usually not larger than 0.004 m; therefore, we believe that convective heat transfer can be neglected in analyzing thermal flows in foam glass. This allows a significant simplification of the mathematical model of heat transfer in foam glass.

Thus, the studies show that heat transfer in foam glass depends on conduction heat transfer via the solid phase of foam glass and on molecular and radiation heat transfer via the gaseous phase. Other kinds of heat transfer have an insignificant effect and can be neglected in analyzing heat transfer in foam glass.

## REFERENCES


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